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Measurement of the W boson helicity fractions in the decays of top quark pairs to lepton + jets final states produced in pp collisions at $\sqrt{s} = 8\,\text{TeV}$

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ABSTRACT

The W boson helicity fractions from top quark decays in $\mathrm{t\bar{t}}$ events are measured using data from proton–proton collisions at a centre-of-mass energy of 8 TeV. The data were collected in 2012 with the CMS detector at the LHC, corresponding to an integrated luminosity of $19.8\,\mathrm{fb}^{-1}$. Events are reconstructed with either one muon or one electron, along with four jets in the final state, with two of the jets being identified as originating from b quarks. The measured helicity fractions from both channels are combined, yielding $F_0 = 0.681 \pm 0.012\,(\text{stat}) \pm 0.023\,(\text{syst})$, $F_\mathrm{L} = 0.323 \pm 0.008\,(\text{stat}) \pm 0.014\,(\text{syst})$, and $F_\mathrm{R} = -0.004 \pm 0.005\,(\text{stat}) \pm 0.014\,(\text{syst})$ for the longitudinal, left-, and right-handed components of the helicity, respectively. These measurements of the W boson helicity fractions are the most accurate to date and they agree with the predictions from the standard model.

1. Introduction

The data from proton–proton (pp) collisions produced at the CERN LHC provide an excellent environment to investigate properties of the top quark, in the context of its production and decay, with unprecedented precision. Such measurements enable rigorous tests of the standard model (SM), and deviations from the SM predictions would indicate signs of possible new physics [1–4].

In particular, the W boson helicity fractions in top quark decays are very sensitive to the Wtb vertex structure. The W boson helicity fractions are defined as the partial decay rate for a given helicity state divided by the total decay rate: $F_{\mathrm{L,R,0}} \equiv \Gamma_{\mathrm{L,R,0}}/\Gamma$, where F_L, F_R, and F_0 are the left-handed, right-handed, and longitudinal helicity fractions, respectively. The helicity fractions are expected to be $F_0 = 0.687 \pm 0.005$, $F_\mathrm{L} = 0.311 \pm 0.005$, and $F_\mathrm{R} = 0.0017 \pm 0.0001$ at next-to-next-to-leading order (NNLO) in the SM, including electroweak effects, for a top quark mass $m_\mathrm{t} = 172.8 \pm 1.3\,\text{GeV}$ [5]. Anomalous Wtb couplings, i.e. those that do not arise in the SM, would alter these values.

Experimentally, the W boson helicity can be measured through the study of angular distributions of the top quark decay products. The helicity angle θ^* is defined as the angle between the direction of either the down-type quark or the charged lepton arising from the W boson decay and the reversed direction of the top quark, both in the rest frame of the W boson. The distribution for the cosine of the helicity angle depends on the helicity fractions in the following way,

$$\begin{aligned}\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} = \; & \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_\mathrm{L} \\ & + \frac{3}{4}(\sin\theta^*)^2 F_0 \\ & + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_\mathrm{R}.\end{aligned} \quad (1)$$

This dependence is shown in Fig. 1 for each contribution separately, normalised to unity, and for the SM expectation. Charged leptons (or down-type quarks) from left-handed W bosons are preferentially emitted in the opposite direction of the W boson, and thus tend to have lower momentum and be closer to the b jet from the top quark decay, as compared to charged leptons (or down-type quarks) from longitudinal or right-handed W bosons.

The measurement of the W boson helicity is sensitive to the presence of non-SM couplings between the W boson, the top quark, and the bottom quark. A general parametrisation of the Wtb vertex can be expressed as [1,6]

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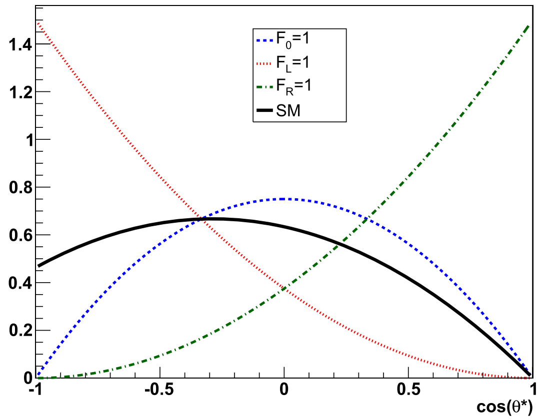

Fig. 1. Predicted $\cos\theta^*$ distributions for the different helicity fractions. The distributions for the fractions F_0, F_L, and F_R are shown as dashed, dotted, and dash-dotted lines, respectively, and the sum of the three contributions according to the SM predictions is displayed as a solid line.

$$\mathcal{L}_{\mathrm{Wtb}} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})tW^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_{\mathrm{W}}}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\,t\,W^{-}_{\mu} + \text{h.c.}, \tag{2}$$

where V_L, V_R, g_L, g_R are vector and tensor couplings (complex constants), $q = p_t - p_b$, and p_t (p_b) is the four-momentum of the top quark (b quark), P_L (P_R) is the left (right) projection operator, and h.c. denotes the Hermitian conjugate. Hermiticity conditions on the possible dimension-six Lagrangian terms also impose $\mathrm{Im}(V_L) = 0$ [7]. In the SM and at tree level, $V_L = V_{tb}$, where $V_{tb} \approx 1$ is the Cabibbo–Kobayashi–Maskawa matrix element connecting the top and the bottom quarks and $V_R = g_L = g_R = 0$. The relationships between the W boson helicity fractions and the anomalous couplings including dependences on the b quark mass are given in Ref. [8].

The helicity fractions of W bosons in top quark decays were first measured at the Tevatron Collider [9–11]. They have been also measured at the LHC, using samples containing $\mathrm{t\bar{t}}$ events obtained in pp collisions at 7 TeV, and having either one [12,13] or two [12] charged leptons in the final state. The CMS Collaboration also reported measurements using event topologies that contain one single reconstructed top quark [14], in pp collisions at 8 TeV. Limits on anomalous couplings have also been reported, derived from W boson helicity measurements [12–14], and from single top quark differential cross section production measurements [15].

This Letter describes a measurement of the W boson helicity fractions in $\mathrm{t\bar{t}}$ events involving one lepton and multiple jets, $\mathrm{t\bar{t}} \to (\mathrm{W^+b})\ (\mathrm{W^-\bar{b}}) \to (\ell^+\nu_\ell \mathrm{b})\ (\mathrm{q\bar{q}'\bar{b}})$, and its charge conjugate, where ℓ is an electron or a muon, including those from leptonic decays of a tau lepton. Final states corresponding to such processes are referred to as lepton + jets. The measurement relies on the analysis strategy described in Ref. [13]. The measurement is performed using pp collisions at centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of $19.8\,\mathrm{fb}^{-1}$, collected during 2012 by the CMS detector.

2. The CMS detector

The CMS detector is a multipurpose apparatus of cylindrical design with respect to the proton beams. The main features of the detector relevant for this analysis are briefly described here. Charged particle trajectories are measured by a silicon pixel and strip tracker, covering the pseudorapidity range $|\eta| < 2.5$. The inner tracker is immersed in a 3.8 T magnetic field provided by a superconducting solenoid of 6 m in diameter that also encompasses several calorimeters. A lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadronic calorimeter surround the tracking volume and cover the region $|\eta| < 3$. Quartz fibre and steel hadron forward calorimeters extend the coverage to $|\eta| \leq 5$. Muons are identified in gas ionisation detectors embedded in the steel return yoke of the magnet. The data for this analysis are recorded using a two-level trigger system. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [16].

3. Data and simulated samples

Signal events corresponding to top quark pairs that decay to lepton + jets final states are expected to contain one isolated lepton (electron or muon) together with at least four jets, two of which originate from b quark fragmentation. Such events are referred to separately as e + jets or μ + jets, respectively, or when combined as ℓ + jets. Background events containing a single isolated lepton and four reconstructed jets arise mainly from processes that produce events containing a single top quark, processes that produce multijet events in association with a W boson that decays leptonically (W + jets), or Drell–Yan processes accompanied by multiple jets (DY + jets) when one of the leptons is misidentified as a jet or goes undetected. Multijet processes can also mimic lepton + jets final states, if a jet is reconstructed as an electromagnetic shower or, more unlikely, if a nonprompt muon from a hadron decay in flight fulfils all identification criteria of a prompt muon.

Simulated Monte Carlo (MC) samples, interfaced with GEANT4 [17], are used to account for detector resolution and acceptance effects, as well as to estimate the contribution from background processes that have characteristics similar to lepton + jets final states in $\mathrm{t\bar{t}}$ decays. A signal $\mathrm{t\bar{t}}$ sample, which also provides a reference for the SM (see Eq. (5)), is simulated using MADGRAPH v5.1.3.30 [18] with matrix elements having up to three extra partons in the final state. The parton distribution function (PDF) set CTEQ6L1 [19] is used when simulating this reference $\mathrm{t\bar{t}}$ sample. The MADGRAPH generator is interfaced with PYTHIA v6.426 [20], tune Z2* [21], to simulate hadronisation and parton fragmentation, and also with TAUOLA v27.121.5 [22] to simulate τ lepton decays. This SM reference $\mathrm{t\bar{t}}$ sample is simulated assuming $m_t = 172.5$ GeV, which results in the following leading-order (LO) W boson helicity fractions for that sample:

$$F_0^{\mathrm{SM}} = 0.6902, \quad F_{\mathrm{L}}^{\mathrm{SM}} = 0.3089, \quad F_{\mathrm{R}}^{\mathrm{SM}} = 0.0009. \tag{3}$$

Single top quark events in the s, t, and tW channels are generated using POWHEG v1.0 [23] and PYTHIA interfaced with TAUOLA, with the PDF set CTEQ6M [19]. Background W + jets and DY + jets processes are simulated using MADGRAPH with the PDF set CTEQ6L1, followed by PYTHIA for fragmentation and hadronisation. Finally, background multijet processes are simulated using the PYTHIA event generator.

Corrections are applied to the simulated samples so that resolutions, energy scales, and efficiencies as functions of p_T and η of jets [24] and leptons [25] measured in data are well described. The effect of multiple pp collisions occurring in the same bunch crossing (pileup) is also taken into account in the simulation.

The data samples selected for this measurement were recorded using inclusive single-lepton triggers, which require at least one isolated electron (muon) with $p_T > 27$ (24) GeV, used to define the e + jets (μ + jets) data sample.

The decay products of candidate top quarks are reconstructed using the CMS particle-flow (PF) algorithm, described in detail elsewhere [26,27]. Individual charged particles identified as coming from pileup interactions are removed from the event. Effects of neutral particles from pileup interactions are mitigated by applying corrections based on event properties. Leptons are required to originate from the primary vertex of the event [28]. A lepton is determined to be isolated using a variable computed as the total transverse momentum of all particles (except the lepton itself) contained within a cone of radius 0.4, centred on the lepton direction, relative to the transverse momentum of the lepton. Electrons are identified by using a multivariate analysis (MVA) [29] based on information from the inner tracker and the ECAL. Events are selected for the e + jets data sample if the identified electron has an MVA discriminant value greater than 0.9, is determined to be isolated, has $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, and $|\eta| < 2.5$. Muons are identified by matching information from the inner tracker and the muon spectrometer [30]. Events are selected for the μ + jets data sample if they contain an isolated muon, $p_{\mathrm{T}} > 26\,\mathrm{GeV}$, and $|\eta| < 2.1$. Events with at least one additional isolated electron or muon are vetoed to reject backgrounds from dileptonic decay modes of $\mathrm{t\bar{t}}$ and DY + jets processes. Jets are reconstructed [24] using the anti-k_{T} clustering algorithm [31], with a distance parameter of 0.5. The selected or vetoed leptons described above are not allowed to be clustered into jets, to avoid ambiguities.

The event selection requires at least four reconstructed jets having $|\eta| < 2.4$, of which the four most energetic jets are required to have p_{T} higher than 55, 45, 35, and 20 GeV. Events with additional jets are not vetoed. The transverse momentum imbalance of the event $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is determined by summing the negative transverse momentum over all reconstructed particles, excluding those charged particles not associated with the primary vertex.

The transverse mass of the W boson is defined as $M_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi))}$, where p_{T}^{ℓ} is the transverse momentum of the lepton, $p_{\mathrm{T}}^{\mathrm{miss}}$ is the magnitude of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, and $\Delta\phi$ is the angle in the (x, y) plane between the direction of the lepton and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$. To reduce the multijet background and suppress dilepton events from $\mathrm{t\bar{t}}$ processes, events are required to have $30 < M_{\mathrm{T}} < 200\,\mathrm{GeV}$. All backgrounds are further suppressed by requiring that at least two jets be identified as originating from b quarks. All jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ are considered as b quark candidates, including those that are not among the four most energetic.

The combined secondary vertex algorithm [32,33] tags b quark jets with an efficiency of about 70% and mistags jets originating from gluons, u, d, or s quarks with a probability of about 1%, for the typical p_{T} ranges (30–100 GeV) probed in $\mathrm{t\bar{t}}$ events. Charm jets have a probability of ≈20% of being tagged as b quark jets. The residual multijet backgrounds, already strongly suppressed by the b tagging requirement described above, are estimated by normalising simulated event samples to yields in control data samples. The control samples are defined by selection criteria which are similar to those for the signal, but which have no b tagging requirement, and have $M_{\mathrm{T}} < 30\,\mathrm{GeV}$ for the μ + jets channel or have an electron MVA discriminant value smaller than 0.5 for the e + jets channel. The estimated amount of multijet events is ≈2% of the e + jets sample, and less than 1% of the μ + jets sample. The contributions of all other residual backgrounds are determined using simulation.

4. Reconstruction of the $\mathrm{t\bar{t}}$ system and reweighting method

The reconstruction of the $\mathrm{t\bar{t}}$ system, described in detail in Ref. [13], relies on testing the selected lepton, the measured $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, and all selected jets for their compatibility with the top quark decay products from the leptonic ($\mathrm{t} \to \mathrm{bW} \to \mathrm{b}\ell\nu$) and hadronic ($\mathrm{t} \to \mathrm{bW} \to \mathrm{bq\bar{q}'}$) branches. The unmeasured component of the neutrino momentum p_z^{ν} is determined by requiring the $\mathrm{t\bar{t}}$ system to be consistent with the invariant masses of two top quarks and two W bosons. With these constraints, b jets are correctly assigned to the leptonic (hadronic) branch in about 74% (71%) of signal events. After the assignment, a kinematic fit is performed, where the momenta of the measured jets and lepton are allowed to vary within their resolutions to better comply with the mass constraints, leading to an improved determination of p_z^{ν} and a more accurate reconstruction of the $\mathrm{t\bar{t}}$ system. In about 5–7% of the selected events, the fit fails to find a solution that is compatible with the constraints and such events are discarded. The number of data events passing all selection criteria, including the fit convergence, is 71 458 in the e + jets sample and 70 986 in the μ + jets sample. A study using simulations normalised to the most precise theoretical cross sections available to date [34–37] indicates that the final sample composition is largely dominated by $\mathrm{t\bar{t}}$ events, with about 82% of events from the ℓ + jets decay mode, ≈10% from other decay modes (including τ leptons), and ≈3.5% of the events from single top quark processes. The remaining events come from backgrounds not containing top quarks in the final state.

The method [13] employed to measure the W boson helicity fractions $(F_{\mathrm{L}}, F_0, F_{\mathrm{R}}) \equiv \vec{F}$ consists of maximising a binned Poisson likelihood function constructed using the number of observed events in data $N_{\mathrm{data}}(i)$ and expected events from MC simulation $N_{\mathrm{MC}}(i; \vec{F})$, in each bin i of the reconstructed $\cos\theta^*_{\mathrm{rec}}$ distribution,

$$\mathcal{L}(\vec{F}) = \prod_i \frac{N_{\mathrm{MC}}(i; \vec{F})^{\,N_{\mathrm{data}}(i)}}{\left[N_{\mathrm{data}}(i)\right]!} \exp\left[-N_{\mathrm{MC}}(i; \vec{F})\right]. \tag{4}$$

While the charged lepton is easily identified in the leptonic branch of $\mathrm{t\bar{t}}$ decays, the down-type quark jet arising from the W boson decay in the hadronic branch of $\mathrm{t\bar{t}}$ decays can not be experimentally distinguished from the up-type quark jet. Due to this ambiguity, only the absolute value $|\cos\theta^*_{\mathrm{rec}}|$ can be reconstructed for the hadronic branch. Hence, only the leptonic branch measurement of $\cos\theta^*_{\mathrm{rec}}$ is used in this analysis. The expected numbers of events from background processes, $N_{\mathrm{W+jets}}(i)$, $N_{\mathrm{DY+jets}}(i)$, and $N_{\mathrm{multijet}}(i)$ represent W boson production in association with multiple jets, Drell–Yan production in association with multiple jets, and production of multiple jets, which do not depend on the W boson helicity fractions. For the processes containing top quarks, the number of expected events in a given bin i is modified by reweighting each event in that bin by a factor w, defined for each decaying branch as

$$w_{\mathrm{lep/had/single\text{-}t}}(\cos\theta^*_{\mathrm{gen}}; \vec{F}) \equiv \left[\frac{3}{8} F_{\mathrm{L}} (1 - \cos\theta^*_{\mathrm{gen}})^2 + \frac{3}{4} F_0 \sin^2\theta^*_{\mathrm{gen}} + \frac{3}{8} F_{\mathrm{R}} (1 + \cos\theta^*_{\mathrm{gen}})^2\right] \Big/ \left[\frac{3}{8} F_{\mathrm{L}}^{\mathrm{SM}} (1 - \cos\theta^*_{\mathrm{gen}})^2 + \frac{3}{4} F_0^{\mathrm{SM}} \sin^2\theta^*_{\mathrm{gen}} + \frac{3}{8} F_{\mathrm{R}}^{\mathrm{SM}} (1 + \cos\theta^*_{\mathrm{gen}})^2\right], \tag{5}$$

where θ^*_{gen} is the helicity angle (specified at matrix element level) of a particular decay branch, and $F_{\mathrm{L}}^{\mathrm{SM}}$, F_0^{SM}, $F_{\mathrm{R}}^{\mathrm{SM}}$ are given in Eq. (3). Therefore, the number of expected events, as a function of the helicity fractions to be measured, is

Table 1
Systematic uncertainties on the measurements of the W boson helicity fractions from lepton + jets events. The cases in which the statistical precision of the limited sample size was assigned as systematic uncertainties are denoted by the symbol (*).

	e + jets		μ + jets		ℓ + jets	
	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_0$	$\pm\Delta F_L$
JES	0.004	0.003	0.005	0.003	0.005	0.003
JER	0.001	0.002	0.004	0.003	0.003	0.003
b tagging eff.	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Lepton eff.	0.001	0.002	0.001	0.001	0.001	0.001
Single top normal.	0.002	$<10^{-3}$	0.003	0.001	0.003	0.001
W + jets bkg.	0.008	0.001	0.007	0.001	0.007	0.001
DY + jets bkg.	0.002	$<10^{-3}$	0.001	$<10^{-3}$	0.001	$<10^{-3}$
Multijet bkg.	0.023	0.007	0.007	0.003	0.008	0.001
Pileup	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$
Top quark mass	0.012	0.008	0.010 (*)	0.008 (*)	0.010	0.007
$t\bar{t}$ scales	0.011	0.008 (*)	0.014	0.007 (*)	0.012	0.007
$t\bar{t}$ match. scale	0.011 (*)	0.007 (*)	0.010	0.007	0.009	0.007
$t\bar{t}$ MC and hadronisation	0.015	0.009	0.005	0.003	0.006	0.004
$t\bar{t}$ p_T reweight	0.011	0.010	$<10^{-3}$	0.001	$<10^{-3}$	0.002
Limited MC size	0.002	0.001	0.002	0.001	0.002	0.001
PDF	0.004	0.001	0.002	0.001	0.002	0.001
Total	0.037	0.020	0.024	0.014	0.023	0.014

$$\begin{aligned} N_{\mathrm{MC}}(i;\vec{F}) = \quad & N_{t\bar{t}}(i;\vec{F}) \\ & + N_{\text{single-t}}(i;\vec{F}) \\ & + N_{\mathrm{W+jets}}(i) \\ & + N_{\mathrm{DY+jets}}(i) \\ & + N_{\text{multijet}}(i), \end{aligned} \tag{6}$$

where

$$\begin{aligned} N_{t\bar{t}}(i;\vec{F}) &= \mathcal{F}_{t\bar{t}} \left[\sum_{t\bar{t} \text{ events in bin } i} w_{\mathrm{lep}}(\cos\theta^*_{\mathrm{gen}};\vec{F}) \right. \\ & \qquad \left. \times\, w_{\mathrm{had}}(\cos\theta^*_{\mathrm{gen}};\vec{F}) \right], \\ N_{\text{single-t}}(i;\vec{F}) &= \sum_{\text{single-t events in bin } i} w_{\text{single-t}}(\cos\theta^*_{\mathrm{gen}};\vec{F}) \end{aligned} \tag{7}$$

represent the expected number of events fulfilling event selection criteria for processes involving top quark pair, and single top quark production, respectively. The normalisation factor $\mathcal{F}_{t\bar{t}}$ for the $t\bar{t}$ sample is a single free parameter in the fit across all bins. The expected cross section for the simulated reference $t\bar{t}$ sample is $252.9^{+13.3}_{-14.5}$ pb, calculated at NNLO and next-to-next-to-leading-log (NNLL) accuracy [34,35], and describes the data well. The fitted values of $\mathcal{F}_{t\bar{t}}$ in both e + jets and μ + jets channels are compatible with 1.00 within 3%. The overall normalisation factor for simulated single top quark events is not modified in the fit and the uncertainty in the assumed cross section is considered as a source of systematic uncertainty. Finally, the unitarity constraint ($F_L + F_0 + F_R = 1$) is imposed, so that one of the helicity fractions, namely F_R, is bound by the measurement of the other two.

The method was validated using pseudo-experiments, where the fitting procedure was performed on pseudo-data, mimicking altered helicity fractions. Linearity tests show that the fitting procedure correctly retrieves the helicity fractions of altered input values for $F_0 \in [0.50, 0.85]$ and $F_L \in [0.20, 0.50]$. Likewise the corresponding statistical uncertainties were verified using sets of statistically uncorrelated pseudo-data.

5. Systematic uncertainties

Systematic effects which could potentially bias the measurement of the W boson helicity fractions have been investigated and their corresponding uncertainties determined, as presented in Table 1.

Residual corrections are applied in simulation to the jet energy scale (JES), to account for differences between data and simulation. The momenta of the jets in simulation are also smeared so that the jet energy resolution (JER) in simulation agrees with that in data. These corrections and smearings are propagated into $\vec{p}_T^{\text{miss}}$ to correct its momentum scale. The uncertainties [24] associated with the JES and JER corrections are also propagated to $\vec{p}_T^{\text{miss}}$, and the full analysis, including the $t\bar{t}$ reconstruction and the resulting measurements of the W boson helicity fractions, is repeated. Scale factors are used to correct the b tagging efficiency in simulation, where those corrections are shifted by their estimated uncertainties, and the full analysis repeated. Scale factors are also used to correct leptons for their identification, isolation and trigger efficiencies, which are varied within their uncertainties so as to maximise potential shape variations of the predicted $\cos\theta^*$ distributions.

To account for any possible bias of the W boson helicity measurements due to uncertainties in the normalisation of simulated backgrounds, the assumed cross section for each sample is varied individually [13]. An uncertainty of 30% is used for the normalisation of DY + jets, single top quark, and W boson production in association with light-quark or gluon jet production. Since the modelling of the simulated heavy-flavour content of the W + jets sample is known to be inaccurate, an uncertainty of $^{+100\%}_{-50\%}$ is assumed for simulated events involving a W boson produced in association with b quark jets. The impact of the DY + jets normalisation uncertainty in the analysis is small, since it corresponds to only a few percent of the sample composition. The normalisation of the multijet background is estimated from control samples and results in an uncertainty of $^{+50\%}_{-50\%}$ in the e + jets channel and $^{+40\%}_{-50\%}$ in the μ + jets channel. Shape uncertainties on the multijet background templates were investigated by comparing the distributions in several different control regions, both in MC and in data, and were found to be negligible, compared to the much larger normalisation uncertainties.

Several uncertainties from possible systematic effects related to theoretical modelling of the signal are estimated by replacing the default $t\bar{t}$ samples with alternative $t\bar{t}$ samples and repeating the entire analysis. Specifically, for the MadGraph interfaced with PYTHIA event generation, the default m_t value of 172.5 GeV is shifted up and down by 1 GeV; the renormalisation and fac-

Table 2
Measurements of the W boson helicity fractions from lepton + jets final states in $t\bar{t}$ decays. The helicity fractions F_0 and F_L are measured simultaneously and are strongly anti-correlated, as indicated by a correlation coefficient $\rho_{0,L}$, because F_R is derived from the unitarity condition.

Channel	$F_0 \pm (\text{stat}) \pm (\text{syst})$	$F_L \pm (\text{stat}) \pm (\text{syst})$	$F_R \pm (\text{stat}) \pm (\text{syst})$	$\rho_{0,L}$
e + jets	$0.705 \pm 0.013 \pm 0.037$	$0.304 \pm 0.009 \pm 0.020$	$-0.009 \pm 0.005 \pm 0.021$	-0.950
μ + jets	$0.685 \pm 0.013 \pm 0.024$	$0.328 \pm 0.009 \pm 0.014$	$-0.013 \pm 0.005 \pm 0.017$	-0.957
ℓ + jets	$0.681 \pm 0.012 \pm 0.023$	$0.323 \pm 0.008 \pm 0.014$	$-0.004 \pm 0.005 \pm 0.014$	-0.959

torisation scales are varied down (up) by a factor of 0.5 (2); the kinematic scale used to match jets to partons (matching threshold) is varied down (up) by factor of 0.5 (2); finally, the parton shower and hadronisation modelling is studied in a $t\bar{t}$ sample simulated with MC@NLO v3.41 [38] using the PDF set CTEQ6M and interfaced with HERWIG v6.520 [39].

Uncertainties in the helicity fractions arising from the limited size of the simulated $t\bar{t}$ samples are taken into account, both in the main analysis and in the determination of the modelling uncertainties. In the former case, these effects are added as a separate source of uncertainty. In the latter case, the systematic uncertainties in the W boson helicity are assigned to be the larger of either (i) the statistical precision of the limited sample size or (ii) the systematic shift of the central value with respect to the reference $t\bar{t}$ sample.

The shape of the p_T spectrum for top quarks, as measured by the differential cross section for top quark pairs [25,40], has been found to be softer than the predictions from MADGRAPH simulation. The effect of this mismodelling is estimated by reweighting the events in the simulated $t\bar{t}$ sample, so that the top quark p_T at parton level in the MC describes the unfolded data distribution. Further, the systematic effects due to the PDFs used to simulate the signal and background samples are estimated according to the prescriptions described in [41,42], using NNPDF21 [43] and MSTW2008lo68cl [44] PDF sets as alternatives to those used at generation. Finally, uncertainties related to the modelling of the pileup in simulated events are also taken into account.

The total systematic uncertainty is given by the sum in quadrature of all uncertainties described above.

6. Results

The measurements of the W boson helicity fractions, using $\cos\theta^*$ from the leptonic branch of $t\bar{t}$ events that decay into e + jets or μ + jets, including the full combination of these two measurements, are shown in Table 2. Within an individual channel, the helicity parameters F_0 and F_L are fit simultaneously, but they are strongly anti-correlated due to the unitarity constraint $F_L + F_0 + F_R = 1$, as indicated by the statistical correlation coefficient $\rho_{0,L}$ given in the table. The separate helicity measurements from the e + jets and μ + jets channels are combined into a single ℓ + jets measurement using the BLUE method [45,46], taking into account all uncertainties and their possible correlations. Uncertainties related to lepton efficiency, multijet background estimations, and statistical uncertainties are considered uncorrelated between the e + jets and μ + jets analyses, while all other uncertainties are assumed to be fully correlated. The combined ℓ + jets measurement of the helicity fractions is dominated by the μ + jets channel, with weights more than double those of the e + jets channel. The χ^2 of the combination is 2.13 for 2 degrees of freedom, corresponding to a probability of 34.5%. The measurement uncertainties are dominated by systematic effects that are correlated between both the e + jets and μ + jets channels. The combined F_0 and F_L values are anti-correlated with a statistical correlation coefficient $\rho_{0,L} = -0.959$. The total correlation coefficient, considering both statistical and systematic uncertainties, is found to be -0.870.

The measured helicity fractions presented in Table 2 are consistent with the SM predictions given at NNLO accuracy [5]. Fig. 2 shows, separately for the e + jets and μ + jets channels, the distributions for the cosine of the helicity angles from the leptonic branch, which are used in the helicity measurements, and the distributions of the corresponding absolute values from the hadronic branch, for comparison purposes. The simulated samples involving top quarks used in the figure were produced using the measured values for the W boson helicity fractions, as determined from the combined ℓ + jets fit. Left-handed W bosons tend to populate the region at $\cos\theta^* \approx -1$, where the charged lepton overlaps with the b quark. However, the angular separation requirement between leptons and jets removes most of the events near $\cos\theta^* = -1$. Very few events are expected in the region preferred by right-handed bosons, near $\cos\theta^* = +1$. However, due to resolution effects, the reconstructed distribution does not fall as rapidly as expected in that region, where the charged lepton and b quark have opposite directions. For these reasons, the shape of the reconstructed $\cos\theta^*$ distribution differs from that expected in the SM (Fig. 1). These features are well reproduced by the simulation, and taken into account in the measurement.

Using these results, limits on anomalous couplings are obtained by fixing the two vector couplings in Eq. (2) to their SM values, $V_L = 1$ and $V_R = 0$, and choosing the tensor couplings, $\text{Re}(g_L)$ and $\text{Re}(g_R)$, as free parameters. The combined ℓ + jets measurement of the W boson helicity fractions F_0 and F_L is reinterpreted in terms of the tensor couplings, $\text{Re}(g_L)$ and $\text{Re}(g_R)$, using the relationships between the W boson helicity fractions given in Ref. [8].

The W boson helicity measurements are displayed in the (F_0, F_L) plane in Fig. 3 (left), together with their one-dimensional statistical (inner-tick mark) and total (outer-tick mark) error bars. The full two-dimensional confidence level (CL) contours corresponding to 68% (dashed line) and 95% (solid line) probabilities are also displayed for the combined measurement. The SM prediction is shown as a star and lies within the 68% CL contour. The corresponding regions in the $(\text{Re}(g_L), \text{Re}(g_R))$ plane, allowed at 68% (dark contour) and 95% CL (light contour), are shown in Fig. 3 (right), together with the SM value. They are derived from Fig. 3 (left), using the relationships between the W boson helicity fractions and the anomalous couplings given in Ref. [8]. A region near $\text{Re}(g_L) = 0$ and $\text{Re}(g_R) \gg 0$, allowed by the fit but excluded by the CMS single top quark production measurement [47], is not shown.

If the right-handed component F_R is bound to zero, consistently with the SM within the precision of the current measurement, the combined ℓ + jets measurement amounts to $F_0 = 0.661 \pm 0.006\,(\text{stat}) \pm 0.021\,(\text{syst})$. In this case, F_L is obtained via the unitarity constraint and yields $F_L = 0.339 \pm 0.006\,(\text{stat}) \pm 0.021\,(\text{syst})$.

7. Summary

A measurement of the W boson helicity fractions in top quark pair events decaying in the e + jets and μ + jets channels has been presented, using proton–proton collision data at $\sqrt{s} = 8\,\text{TeV}$, and corresponding to an integrated luminosity of $19.8\,\text{fb}^{-1}$. The helicity fractions F_0 and F_L are measured with a precision of

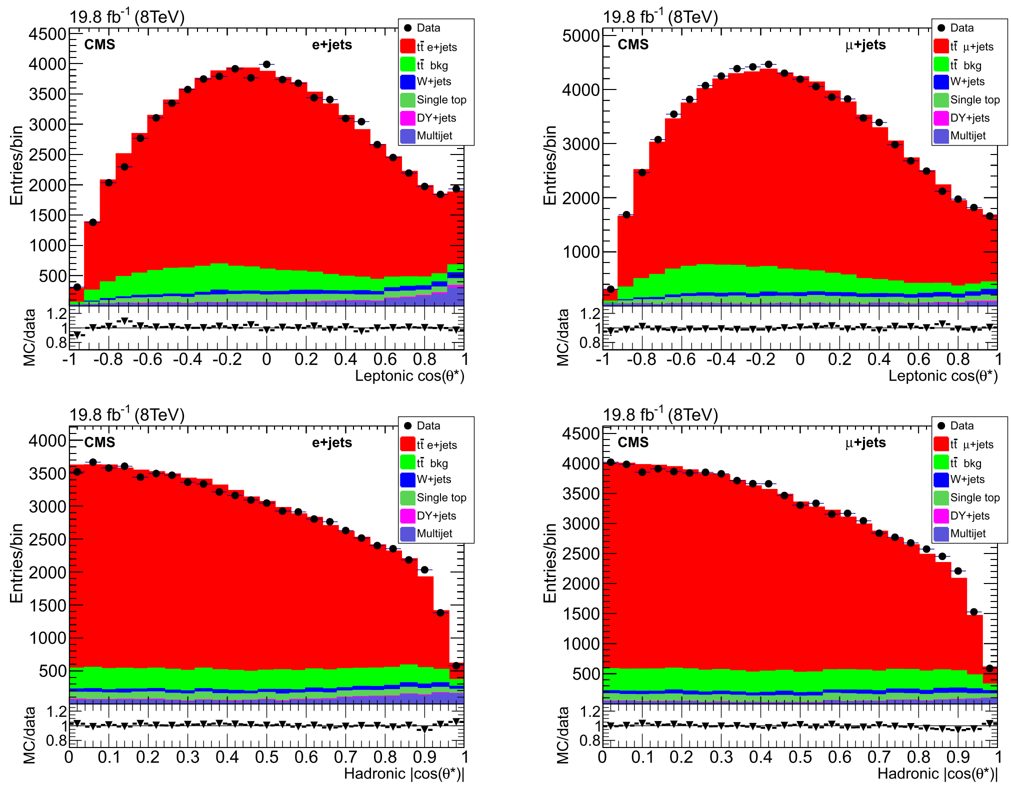

Fig. 2. Distributions for the cosine of the helicity angle in the leptonic (upper row) and hadronic (lower row) branches, for the e + jets (left) and μ + jets (right) decay channels. The combined ℓ + jets post-fit measurements of the helicity fractions were used in the simulation of $t\bar{t}$ and single top quark events. The data are displayed as solid points, simulated samples of $t\bar{t}$ (signal) processes and the contribution from background processes as histograms. At the bottom of each plot, the ratio between MC simulation and data is displayed. The error bars correspond to the statistical uncertainties.

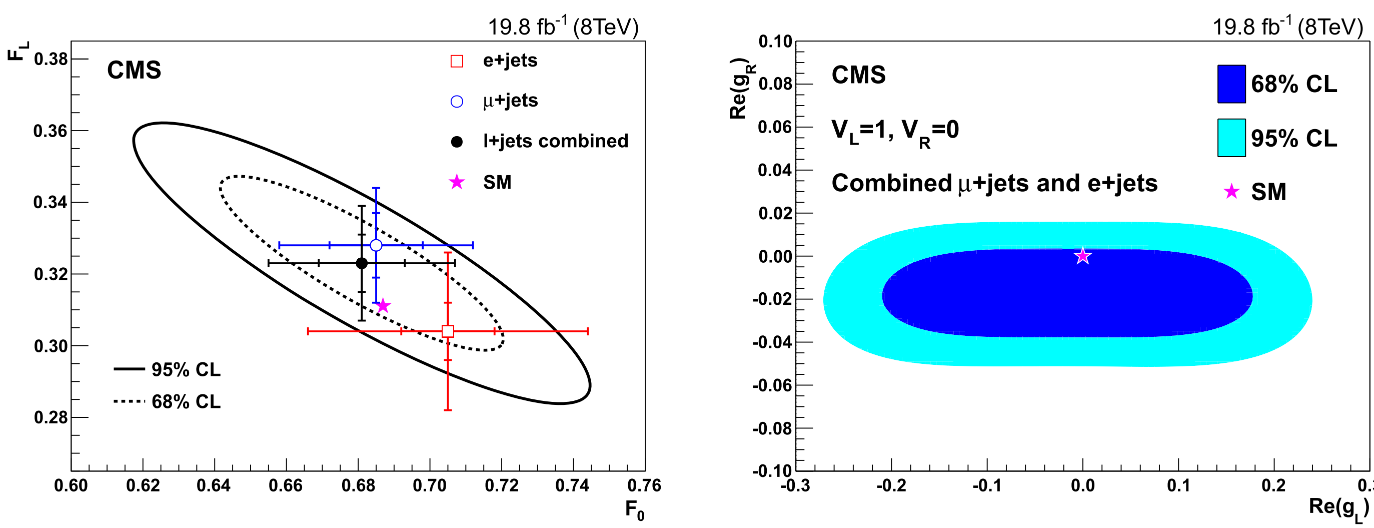

Fig. 3. Left: the measured W boson helicity fractions in the (F_0, F_L) plane. The dashed and solid ellipses enclose the allowed two-dimensional 68% and 95% CL regions, for the combined ℓ + jets measurement, taking into account the correlations on the total (including systematic) uncertainties. The error bars give the one-dimensional 68% CL interval for the separate F_0 and F_L measurements, with the inner-tick (outer-tick) mark representing the statistical (total) uncertainty. Right: the corresponding allowed regions for the real components of the anomalous couplings g_L and g_R at 68% and 95% CL, for $V_L = 1$ and $V_R = 0$. A region near $\mathrm{Re}(g_L) = 0$ and $\mathrm{Re}(g_R) \gg 0$, allowed by the fit but excluded by the CMS single top quark production measurement, is omitted. The SM predictions are shown as stars.

better than 5%, yielding the most accurate experimental determination of the W boson helicity fractions in $t\bar{t}$ processes to date. The measured W boson helicity fractions are $F_0 = 0.681 \pm 0.012\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst})$, $F_L = 0.323 \pm 0.008\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$, and $F_R = -0.004 \pm 0.005\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$, with a correlation coefficient of -0.87 between F_0 and F_L, and they are consistent with the expectations from the standard model.

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